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Abstract

Impacts of uncertain climate forecasts on future regional air quality are investigated using downscaled MM5 meteorological fields from the NASA GISS and MIT IGSM global climate models and the CMAQ model in 2050 in the continental US. Three future climate scenarios: high-extreme, low-extreme and base, are developed for regional air quality simulations. GISS, with the IPCC A1B scenario, is used for the base case. IGSM results, in the form of probabilistic distributions, are used to perturb the base case climate to provide 0.5th and 99.5th percentile climate scenarios. Impacts of the extreme climate scenarios on concentrations of summertime fourth-highest daily maximum 8-h average ozone are predicted to be up to 10 ppbv (about one-eighth of the current NAAQS of ozone) in some urban areas, though average differences in ozone concentrations are about 1–2 ppbv on a regional basis. Differences between the extreme and base scenarios in annualized $PM_{2.5}$ levels are very location dependent and predicted to range between −1.0 and +1.5 $\mu g\,m^{-3}$. Future annualized $PM_{2.5}$ is less sensitive to the extreme climate scenarios than summertime peak ozone since precipitation scavenging is only slightly affected by the extreme climate scenarios examined. Relative abundances of biogenic VOC and anthropogenic NO_x lead to the areas that are most responsive to climate change. Such areas may find that climate change can significantly offset air quality improvements from emissions reductions, particularly during the most severe episodes.

1 Introduction

Impacts of future climate change on regional air quality have been investigated for different regions, future climate and future emission scenarios. Due to uncertainties inherent in climate forecasts, the Intergovernmental Panel on Climate Change (IPCC) addresses multiple scenarios associated with different projections of future anthropogenic emissions of greenhouse gases (GHGs) as a qualitative assessment, which

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are presented in IPCC's Special Report on Emissions Scenarios (SRES) (IPCC, 2001; Nakićenović, 2000). Hogfere et al. (2004) predict an increase in spatially averaged summertime daily maximum 8-h O_3 concentrations of 4.2 ppbv in the 2050s based on IPCC A2 scenario and assuming anthropogenic precursor emissions and boundary conditions to remain constant. Murazaki and Hess (2006) suggest an increase of up to 12 additional days in the northeast of the continental US each year exceeding daily maximum 8-h average ozone concentration of 80 ppbv in the decade 2090s compared with 1990s, assuming that future precursors emissions remain at 1990 levels and GHG emissions follow A1 scenario. Racherla and Adams (2006) predict an increase up to 5 ppbv in ozone concentrations and a 2–18% decrease in fine particulate matter levels between 1900s and 2050s assuming climate will follows the IPCC A2 scenario and anthropogenic emissions remain constant. Sanderson et al. (2003) predict a 10–20 ppbv increase in ozone concentrations due to a combined effect of changes in vegetation and prescribed IPCC IS92a CO_2 emissions in 2090s compared with 1990s.

The objective of this study is to investigate the impact of uncertainties inherent in climate change forecasts on regional air quality predictions over the continental US using multiple climate futures. Given that model inputs (e.g., regional meteorology and precursor emissions) and parameterization/assumption lead to uncertainties in regional downscaling of future climate and air quality modeling (which have been presented elsewhere, e.g., Bergin et al., 1998; Gustafson and Leung, 2007; Hanna et al., 2001; Hanna et al., 2005; Russell and Dennis, 2000), the purpose of this study is not to specifically forecast future air quality but to quantify the impact of climate uncertainties on regional air quality forecasts, particularly focusing on ground-level ozone and $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) due to their adverse health-related effects (Bernard et al., 2001; Galizia and Kinney, 1999; Johnson and Graham, 2005). Of particular interest are the uncertainties associated with the "climate penalty" (increases in levels of air pollutants caused by climate change Mickley et al., 2004) and investigating if uncertainties in climate predictions suggest alternative emission control strategies.

2 Method

2.1 Downscaling of global climate models to a meso-scale meteorological models

The meso-scale meteorological model, MM5 (The Fifth-Generation NCAR/Penn State Mesoscale Model) (Grell G., 1994; Seaman, 2000), is used to downscale outputs from the NASA Goddard Institute of Space Studies (GISS) global climate model (GCM) (Rind et al., 1999) to regional scale for studying effects of climate on regional air quality in year 2050. 2050 is chosen for this study as a compromise between non-trivial climate modification and a reasonable horizon for regional air quality planning. The GISS-MM5 climate fields, following the IPCC A1B scenario, are used as base-case meteorological fields. Details in GISS global climate simulation and downscaling of GISS global climate to meso-scale climate are described by Mickley et al. (2004) and Leung and Gustafson (2005). IPCC A1B assumes a future world of very rapid economic growth with a balanced case between fossil and non-fossil energy sources (Nakićenović, 2000). For assessing uncertainties in climate projections and their associated effects on regional air quality, it is useful to investigate uncertainties in individual, but covering, climate variables (e.g., temperature, absolute humidity, etc.) in terms of their probabilistic distributions instead of qualitative assessments. In this study, climate fields from MIT's Integrated Global System Model (IGSM) simulations (Prinn et al., 1999; Reilly et al., 1999), in the form of probabilistic distributions, are used to quantify uncertainties inherent in forecasts of future changes, and their associated effects on regional air quality.

Temperature and absolute humidity fields from the GISS-MM5 climate are chosen for perturbation as they are strongly correlated with regional ozone and secondary $PM_{2.5}$ levels (Nenes et al., 1998; Seinfeld and Pandis, 1998; Sillman and Samson, 1995; Strader et al., 1999; Wise and Comrie, 2005; Wunderli and Gehrig, 1991). Climate fields used are associated with the, 0.5th, 50th and 99.5th percentiles of temperature and humidity from IGSM. Outputs from the two-dimensional 50th percentile IGSM and the base case GISS-MM5 meteorological fields and boundary conditions are used

to develop perturbation fields for uncertainty analysis. Details are given in the Supplementary Material, and briefly described here. Three-dimensional time-dependent variables of the GISS-MM5 climate are decomposed in a manner similar to Reynolds Decomposition (Eq. 1):

$$C(y,x,z,t) = \overline{C(y,z,m)} + C'(y,x,z,t) \quad (1)$$

where $C(y,x,z,t)$ is the base case GISS-MM5 climate field (resolved hourly and at a fine scale, three dimensionally; $\overline{C(y,z,m)}$ is the longitudinally and monthly average field, $C'(y,x,z,t)$ is the resulting finer scale fluctuating terms, y is latitude, z is altitude, x is longitude, m is month and t is time (from MM5 simulations). To develop the IGSM-derived fields, the base case average term $\overline{C(y,z,m)}$ is replaced with the 0.5th, 50th, and 99.5th percentile IGSM fields, and then the fine-scale, fluctuating field is added. The reconstructed meteorological fields are then used as inputs to rerun MM5 in order to get conservative meteorological fields. Fields derived from the 0.5th and 99.5th percentiles climate are defined as "low-extreme" and "high-extreme" scenarios, respectively. The resulting fields were reanalyzed to assure that similar changes in temperature and humidity remained. It is recognized that using MM5 for downscaling may not capture the full range of uncertainty in climate change, though the new fields do capture the impacts of the temperature and humidity changes, and the precipitation and wind fields are dynamically consistent and responsive to the changes.

2.2 Emission and air quality modeling

MM5 results are inputs to the Sparse Matrix Operating Kernel for Emissions (SMOKE) (http://www.smoke-model.org/index.cfm, last access: 11 January 2008) for estimating emissions of precursors, and to the Community Multiscale Air Quality Model (CMAQ) (Byun, 2006) for simulating impacts of climate uncertainties on regional air quality. Details of the projections of future emissions and regional air quality modeling approach

are given elsewhere (Tagaris et al., 2007; Woo et al., 2008[1]), and summarized here. Projections of emissions for Canada, Mexico and the US account for the US Clean Air Interstate Rule (CAIR) controls (Houyoux, 2004) and projected growth in population and human activities follow the IPCC A1B scenario in 2050. Although the same projected emission inventories are applied in the uncertainty simulations in 2050, simulated emissions of precursors of pollutants for the three climate scenarios are not identical since emissions (especially, biogenic volatile organic compounds (VOCs)) respond to changes in meteorological fields (e.g., temperature, precipitation, etc.).

The simulation domain in this study covers the continental US as well as parts of Canada and Mexico. For more detailed analysis, the continental US is divided into five regions – West, Plains, Midwest, Northeast and Southeast (Fig. 1). The highest daily maximum 8-h average ozone (MDA8hr O_3) levels, which are often associated with adverse health effects in epidemiologic studies and used for assessing attainment of the US National Ambient Air Quality Standards (NAAQS) for ozone (Bernard et al., 2001; Levy et al., 2001), consistently occur in summer. Three summer months (June, July and August) in the year 2050 are chosen as the target period for studying the impact of climate uncertainties on the average and 4th highest MDA8hr O_3 (4th MDA8hr O_3) concentrations. The 4th highest value is also chosen as being more stably predicted by chemical transport models than is the maximum in any location. For $PM_{2.5}$, one month from each of the four seasons (i.e., January, April, July and October) in 2050 is chosen for studying the impact of climate uncertainties on annualized $PM_{2.5}$ levels because $PM_{2.5}$ has distinct seasonal variation and has an annual health-based standard (http://www.epa.gov/air/criteria.html, last access: 11 January 2008) .

[1]Woo, J. H., He, S. P., Amar, P., Tagaris, E., Manomaiphiboon, K., Liao, K. J., and Russell, A. G.: Development of a Future Emissions Inventory for Assessing Global Climate Change Impacts on Regional Air Quality over North America, J. Air Waste Manage., in revision, 2008.

3 Results and discussions

3.1 Meteorology

The 2050 based case annualized temperatures (average temperatures of January, April, July and October) are predicted to be 0.4–2.4 K warmer than 2001, depending on the region, whereas absolute humidity values are simulated to be approximately 9–14% higher (Table 1). On the other hand, annualized temperatures and absolute humidity of the two 2050 extreme scenarios are predicted to change approximately from −0.8 K (low-extreme) to +2.1 K (high-extreme) and −7% (low-extreme) to +19% (high-extreme), respectively, as compared with the 2050 base scenario on a regional basis (Table 1). Summer (JJA) temperatures and absolute humidity values are predicted to be higher for the 2050 base case than 2001 climate (Table 1). Differences between the high-extreme and base scenarios are found to be larger than differences between the low-extreme and base scenarios for both temperature and absolute humidity. This reflects that the probability density functions of predicted temperatures and absolute humidity are not normally distributed but have a long right-hand tail in the IGSM outputs (Table S1) (Webster et al., 2003). Annualized precipitation is found to be somewhat different for the three scenarios, with a notable decrease in summer precipitation in the Plains for the high-extreme scenario as compared with the base case (Fig. 3). http://www.atmos-chem-phys-discuss.net/8/7781/2008/acpd-8-7781-2008-supplement.pdf

3.2 Emissions

Both sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions are forecast to be 51% lower in 2050 compared with emissions in 2001, due to planned emission controls. Ammonia (NH_3) emissions are simulated to increase by about 7% due to increases in population and related human activities. Total volatile organic compounds (VOC) emissions are predicted to increase by about 2% in 2050 as a net result of increased biogenic VOC emissions and lower anthropogenic VOC emissions for the whole sim-

ulation domain (Tagaris et al., 2007; Woo et al., 2008[1]). For the two extreme 2050 scenarios, SO_2, NO_x and NH_3 emissions are predicted to change very slightly compared with the 2050 base scenario (Table S2). However, predicted VOC emissions vary significantly as biogenic VOC emissions are much more sensitive to temperature changes than other precursor emissions (Table 1). Responses of VOC emissions to the extreme climate scenarios are also found to change spatially. The low-extreme scenario results in an approximately 0–17% decrease in total VOC (= anthropogenic + biogenic VOC) emissions compared with the 2050 base scenario. For the high-extreme scenario, higher biogenic VOC emissions cause an increase of up to about 22% in annualized and 29% in summer-average total VOC emissions compared with the base case in 2050 on a regional basis (Table 1). http://www.atmos-chem-phys-discuss.net/8/7781/2008/acpd-8-7781-2008-supplement.pdf

3.3 Summer-average ozone and summertime fourth-highest daily maximum 8-h average ozone

Summer-average ozone and daily maximum 8-h average ozone concentrations are found to be slightly sensitive to the extreme climate scenarios in 2050. Differences in summer-average ozone and daily maximum 8-h average ozone concentrations are about 1–2 ppbv between the extreme and base case climate scenarios on a regional basis (Table 2). For the peak ozone levels, summertime (JJA) 4th MDA8hr O_3 (4th MDA8hr O_3 in the summer of 2050) concentrations for the high-extreme scenario are predicted to increase up to 10 ppbv as compared with the 2050 base case in urban areas of the Northeast, Midwest and Texas in the continental US (Fig. 2). Such differences are attributed to impacts of meteorological changes, especially temperature, humidity and circulation, on the photochemistry of tropospheric ozone. Sensitivity analyses show that peak ground-level ozone levels and ambient temperatures are positively correlated with each other (Aw and Kleeman, 2003; Baertsch-Ritter et al., 2004; Dawson et al., 2007; Menut, 2003). Sillman and Samson (1995) found higher tem-

peratures increase decomposition peroxyacyl nitrates (PANs) and generate nitrogen dioxides (NO_2) during the daytime and hence cause higher peak ozone levels (Sillman and Samson, 1995). Higher absolute humidity (water vapor concentration) increases hydroxyl radicals (OH), resulting in faster oxidation of VOCs, forming peroxy radicals (e.g., HO_2, RO_2) which react with nitrogen oxides (NO) to form NO_2 (Seinfeld and Pandis, 1998). Even when changes in precursor emission are not considered, concentrations of summertime (JJA) 4th MDA8hr O_3 in urban are more sensitive to changes in temperatures and humidity due to their higher concentrations of PANs, VOC, CH_4 and CO, and are also expected to find a greater simulated impact from the high-extreme scenario than the base case in 2050. Moreover, when temperature-induced increases in VOC emissions (especially biogenic VOC emissions, up to ~29% regionally, Table 1) are considered, higher VOC emissions induce more ozone formation in NO_x-saturated (or VOC-sensitive) urban areas (Seinfeld and Pandis, 1998) and the effects of extreme climate scenario are predicted to be more significant. Lower levels of predicted summer precipitation for the high-extreme scenario also lead to more ozone formation and an increase in the differences between the high-extreme and base scenarios in the polluted urban areas (Fig. 3).

Differences in concentrations of summertime 4th MDA8hr O_3 are predicted to be approximately ±3 ppbv between the base case and low-extreme scenario (Fig. 2). Concentrations of summertime 4th MDA8hr O_3 are found to be less sensitive to the low-extreme climate scenario than the high-extreme scenario due to smaller differences in meteorological fields between the base case and low-extreme scenario as well as non-linear responses of ozone concentrations to emission changes (Cohan et al., 2005). Tagaris et al. (2007) present an about 20% decrease in concentrations of summer-average daily maximum 8-h ozone and less number of exceedance days of previous ozone NAAQS of 85 ppbv in five US cities between 2000–2002 and 2049–2051, mainly due to currently planned emission controls in the future. Here, there is a maximum change of 10 ppbv in 4th MDA8hr O_3 (about one-seventh of the current NAAQS of ozone of 75 ppbv) found in 2050 in the extreme climate scenario, which may

significantly offset the effectiveness of currently planned emission reductions in urban areas with high concentrations of PANs, VOC, CH_4 and CO as well as VOC-sensitive ozone formation regimes.

3.4 Annualized $PM_{2.5}$

$PM_{2.5}$ levels are influenced by the changes between the climate scenarios in several ways. Higher temperatures favor semi-volatile compounds (e.g., secondary organic aerosols (SOAs) and ammonium nitrate (NH_4NO_3)) to remain in the gas phase. On the other hand, increases in temperatures and humidity result in higher emissions of SOA precursors and faster oxidation of SO_2, NO_x and VOCs, increasing formation of condensable compounds, such as sulfate, nitrate and semi-volatile organic species (SVOCs). Further, changes in precipitation can have a dramatic effect on frequency of washout and fine particle concentrations (Racherla and Adams, 2006). Overall, the net effects of different mechanisms of $PM_{2.5}$ production and loss result in a -1.0 to $+1.5\,\mu g\,m^{-3}$ difference in annualized $PM_{2.5}$ levels (average of daily $PM_{2.5}$ levels of January, April, July and October) between the extreme and base scenarios in 2050 (Fig. 2). Larger differences in $PM_{2.5}$ levels between the extreme and base scenarios are found in the Southeast and Midwest of the continental US due to higher $PM_{2.5}$ precursor emissions (e.g., anthropogenic SO_2, NO_x, VOC, etc.) in those areas. The changes in $PM_{2.5}$ levels attributed to the extreme climate scenarios are dominated by sulfate and nitrate since SOA formation is not fully captured in current regional air quality models (Morris et al., 2006; Pun and Seigneur, 2007).

Impacts of climate uncertainties on $PM_{2.5}$ concentrations also show a seasonal trend. Monthly-average $PM_{2.5}$ concentrations are predicted to be lower in January but slightly higher in July for the high-extreme scenario compared with the 2050 base case (Table 3); this is mainly because temperatures change the partitioning of semi-volatile compounds between the gas-phase and particle-phase. Higher temperature and humidity increase sulfate aerosol formation due to faster gas- and aqueous-phase oxidation rates of SO_2. Rae et al. (2007) have shown that increases in temperature

and changes in oxidant concentrations are simulated to decrease 1% of Aitken-mode sulfate aerosols but increase of 9.2% of accumulation-mode sulfate in 2100 assuming climate and emission-induced oxidant levels will follow the IPCC SRES A2 scenario. Total sulfate concentrations are expected to increase by 6.8% in 2100 compared with 1990. Effects of climate on nitrate are more complicated than sulfate due to high vapor pressure for particle-phase ammonium nitrate (Seinfeld and Pandis, 1998). Aw and Kleeman (2003) present that nitrate aerosol may slightly increase with cool temperature (<290 K) but decrease with hot temperature (>290 K) as temperature increases. The combined effects of changes in sulfate and nitrates show that the high-extreme climate scenario with associated increases in temperatures in January induces more nitrates to be in the gas-phase lowering $PM_{2.5}$ concentrations. The seasonal trend is reversed in the low-extreme scenario. Wise and Comrie (2005) show that, from a long-term statistical analysis, PM is not as weather-dependent as ozone in the southwestern US since low precipitation is found in the studying region. The results in this study also show that annualized $PM_{2.5}$ levels are not as sensitive as concentrations of summer-time peak ozone with respect to the extreme climate scenarios examined since one of the main removal mechanisms of $PM_{2.5}$, precipitation scavenging, is found to slightly affect annualized $PM_{2.5}$ levels between the extreme climate scenarios (Fig. 3). Our previous study shows that annual average $PM_{2.5}$ levels are predicted to decrease by about 23% as a combined effects of future climate change and CAIR emission controls (Tagaris et al., 2007). The results here imply that future emission controls will still be effective with respect to the extreme climate scenarios if precipitation is only slightly affected.

4 Response of air quality to emission controls under extreme climate scenarios

In addition to simulating how the alternative extreme scenarios impact pollutant levels, we also investigate the responses of ozone and $PM_{2.5}$ levels to emission controls under the extreme climate scenarios. CMAQ with the Decoupled Direct Method-3D (DDM-

3D) (Dunker et al., 2002; Yang et al., 1997), is used to quantify sensitivities of ozone and $PM_{2.5}$ to precursor emissions. First-order sensitivities ($S_{i,j}$) of pollutant concentration i (C_i) (i.e., ozone and $PM_{2.5}$) to source emissions$j$ (E_j) (i.e., anthropogenic VOC, anthropogenic NO_x and total SO_2 emissions) are defined as (Yang et al., 1997):

$$S_{i,j} = E_j \frac{\partial C_i}{\partial E_j} \quad (2)$$

First-order sensitivities represent the locally linear responses of pollutant concentrations to emission changes and have the same units as the concentrations. Sensitivities of summertime 4th MDA8hr O_3 to anthropogenic NO_x emissions (S_{O_3,ANO_x}) are predicted to slightly decrease for the low-extreme scenario but increase for the high-extreme scenario as compared with the base case in 2050. The differences are mainly attributed to the climate effects on biogenic VOC emissions and photochemistry. The effects of the extreme climate scenarios on sensitivities of summertime 4th MDA8hr O_3 to anthropogenic VOC emissions ($S_{O_3,AVOC}$) are predicted to be small. For the responses of $PM_{2.5}$ to emission changesunder the extreme climate scenarios, sensitivities of annualized $PM_{2.5}$ to SO_2 emissions ($S_{PM_{2.5},SO_2}$) are predicted to slightly increase for the high-extreme scenario because of higher temperature, humidity, decreased rainfall in some regions, and faster oxidation of precursors as compared with the base scenario. Higher temperatures for the high-extreme scenario favor particulate NH_4NO_3 to dissociate to its gas phase precursors and cause slight decreases in sensitivities of annualized $PM_{2.5}$ concentrations to anthropogenic NO_x emissions ($S_{PM_{2.5},ANO_x}$) (Fig. 4). Overall, on a regional basis, the effectiveness of NO_x and SO_2 emission controls for reducing peak ozone and $PM_{2.5}$ levels changes little, though climate-driven increases in extreme ozone levels may require additional controls to reach applicable air quality standards.

5 Conclusions

Uncertainties associated with simulations of the extreme climate scenarios are found to have a rather moderate effect on predicted emissions of VOC and concentrations of fourth-highest daily maximum 8-h average ozone in year 2050. Differences in concentrations of fourth-highest daily maximum 8-h average ozone between the extreme climate scenarios and base case are found up to 10 ppbv (about one-seventh of the current ozone standards) in some polluted urban areas due to higher temperature, absolute humidity and VOC emissions, though the change in summer-average ozone is minimal (~1 ppbv). Differences between the extreme and base scenarios in annualized $PM_{2.5}$ levels are predicted to range between −1.0 and +1.5 $\mu g\,m^{-3}$. Future annualized $PM_{2.5}$ is predicted to be less sensitive to the extreme climate scenarios than summertime fourth-highest daily maximum 8-h average ozone since precipitation scavenging is not significantly changed with the extreme climate scenarios. Planned controls for decreasing regional ozone and $PM_{2.5}$ will continue to be effective in the future under the extreme climate scenarios. However, the impact of climate uncertainties may be substantial in some urban areas and should be included in assessing future regional air quality and emission control requirements.

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Table 1. Differences in summer-average and annualized temperatures (K), absolute humidity (%) and total VOC (=anthropogenic + biogenic VOCs) emissions (%) between the three 2050 climate scenarios and 2001.

	Summer-average						Annualized					
	West	Plains	Midwest	Northeast	Southeast	US	West	Plains	Midwest	Northeast	Southeast	US
Temperature (K)												
Base-2001	1.8	0.6	0.2	1.8	0.9	1.0	2.4	1.1	1.0	1.8	0.4	1.3
Low_extreme-Base	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7	−0.7	−0.6	−0.7	−0.8
High_extreme-Base	1.9	2.1	1.8	1.7	1.6	1.9	2.1	2.1	1.8	1.7	1.7	1.9
Absolute Humidity (%)												
Base-2001	55.1	16.5	12.5	12.8	12.8	20.2	12.8	9.4	11.3	13.5	9.0	11.3
Low_extreme-Base	−4.1	−3.8	−4.0	−4.1	−4.0	−4.0	−6.6	−5.7	−5.1	−5.1	−4.7	−5.4
High_extreme-Base	13.3	11.6	11.3	11.6	10.8	11.7	19.1	15.7	13.6	11.9	12.6	15.1
Total VOC Emissions (%)												
Base-2001	16.6	3.5	−16.9	−3.5	5.3	2.3	11.7	−9.1	−26.3	−19.6	−16.9	−11.8
Low_extreme-Base	−17.0	−10.3	0.4	0.1	−6.9	−8.3	−13.9	−9.1	−1.4	−2.4	−4.9	−7.6
High_extreme-Base	4.1	14.9	28.5	24.2	15.6	15.4	6.3	14.0	22.0	12.9	17.1	13.2

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Table 2. Summer-average ozone concentrations (in ppbv) for the three climate scenarios for the five regions and US.

O_3 (ppbv)	Summer-average ozone			Summer-average maximum daily 8-h average ozone		
	Low-extreme	base	High-extreme	Low-extreme	base	High-extreme
West	41.7	41.8	41.6	50.25	50.32	50.51
Plains	40.4	40.8	41.8	48.46	49.33	50.88
Midwest	35.4	35.8	36.7	44.94	46.01	47.19
Northeast	37.1	37.2	37.3	44.04	44.87	44.99
Southeast	42.6	42.9	43.7	52.23	52.73	54.67
US	39.9	40.3	40.9	48.53	49.18	50.30

Table 3. $PM_{2.5}$ concentrations (in $\mu g\,m^{-3}$) for the three climate scenarios in January, April, July and October of 2050 for the five regions and US.

	January			April			July			October		
	Low-extreme	Base	High-extreme	Low-extreme	Base	High-extreme	Low-extreme	Base	High-extreme	Low-extreme	Base	High-extreme
West	3.17	3.13	3.05	2.43	2.44	2.49	2.38	2.41	2.57	3.29	3.30	3.42
Plains	7.23	6.96	6.50	3.39	3.37	3.42	4.26	4.31	4.73	4.18	4.21	4.45
Midwest	14.53	13.53	12.21	5.80	5.78	5.79	6.70	6.65	6.72	6.39	6.38	6.64
Northeast	9.94	9.62	8.70	4.40	4.36	4.32	3.54	3.56	3.76	5.25	5.23	5.48
Southeast	10.46	10.23	9.83	5.68	5.69	5.85	5.65	5.62	5.78	6.90	7.08	7.72
US	8.20	7.86	7.32	3.99	3.98	4.03	4.39	4.40	4.65	4.83	4.87	5.14

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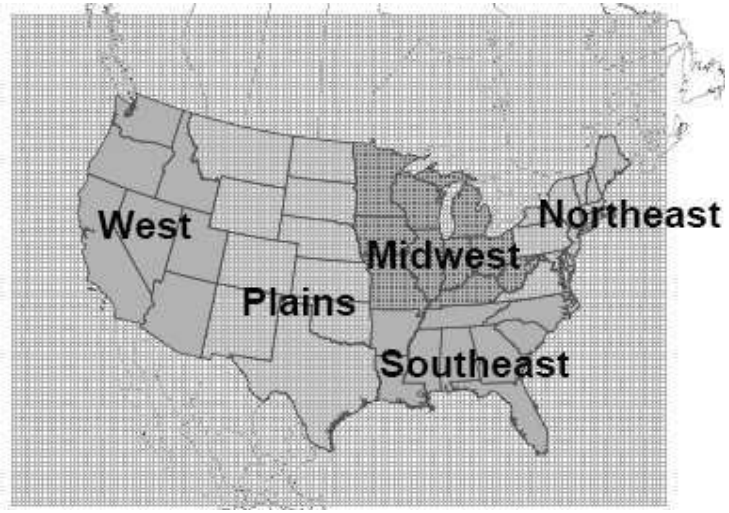

Fig. 1. Simulation domain and US regions.

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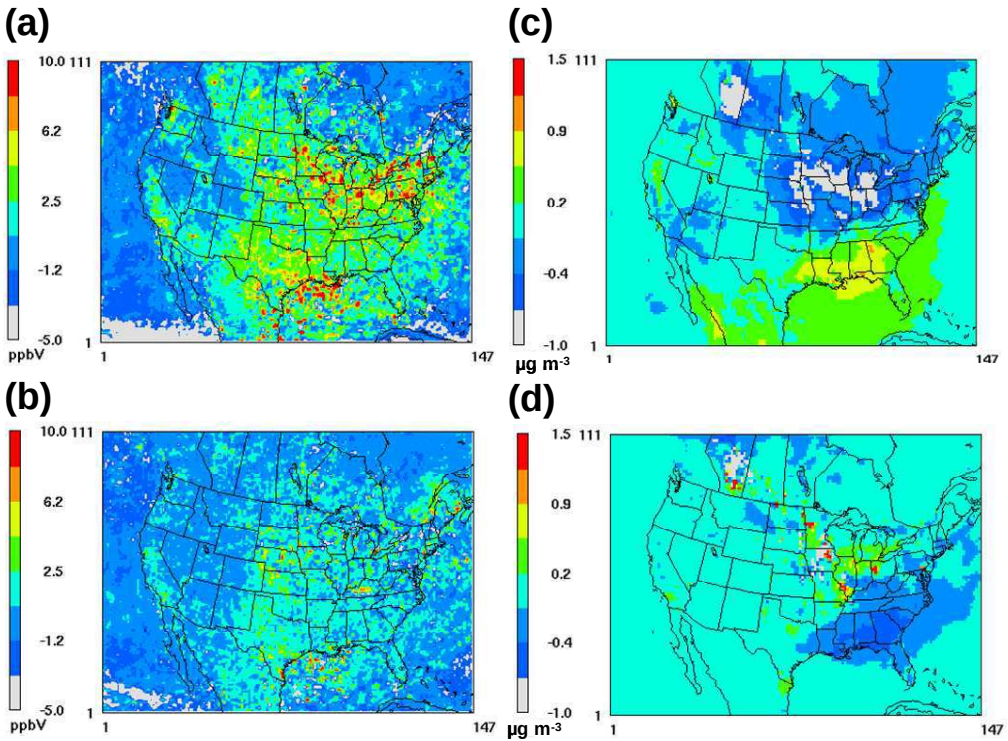

Fig. 2. Differences between the 2050 high-extreme and base scenarios (top), and the 2050 low-extreme and base scenarios (bottom) in summertime 4th MDA8hr O_3 (panels **a** and **b**) and annualized $PM_{2.5}$ (panels **c** and **d**) concentrations, respectively.

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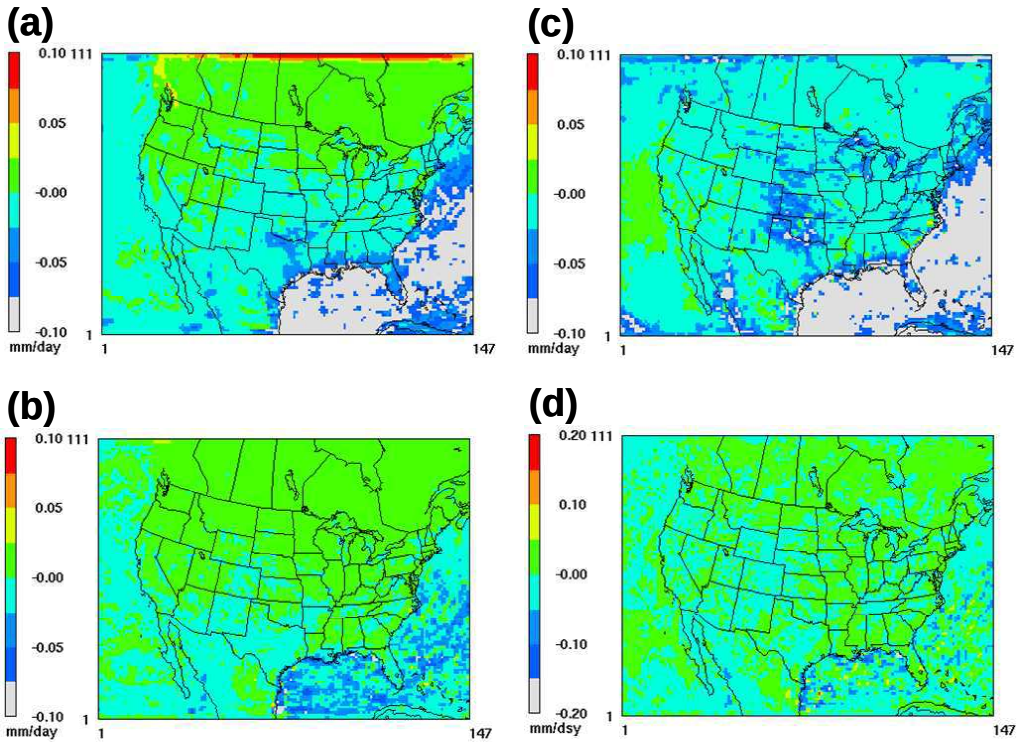

Fig. 3. Spatial distribution of difference in precipitation (mm/d) in 2050 for **(a)** Annualized (high-extreme – base); **(b)** Annualized (base – low-extreme); **(c)** Summer-averaged (high-extreme – base); **(d)** Summer-averaged (base–low-extreme).

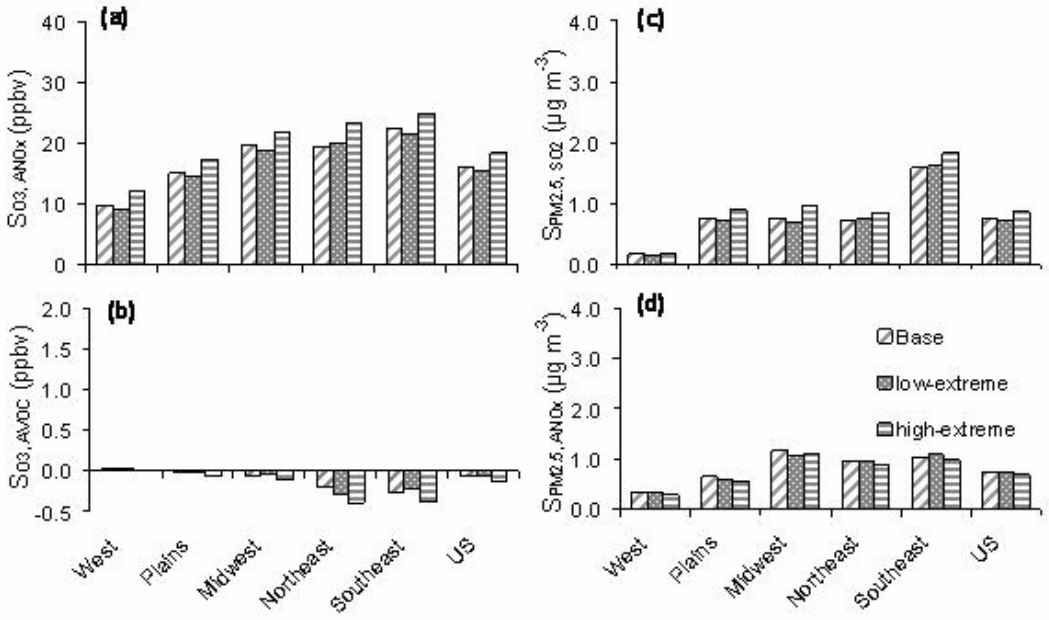

Fig. 4. Sensitivities of 4th MDA8hr O_3 to **(a)** anthropogenic NO_x (S_{O_3,ANO_x}) and **(b)** anthropogenic VOC ($SO_{3,AVOC}$) as well as sensitivities of annualized $PM_{2.5}$ to **(c)** anthropogenic SO_2 ($S_{PM_{2.5},SO_2}$) and **(d)** anthropogenic NO_x ($S_{PM_{2.5},ANO_x}$) for the five regions and US.

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